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Design of Haptic Interface Controller under noise uncertainty and delay condition

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Abstract

Haptic interface is important circuitry to interact with virtual environment. It makes interaction between user and virtual environment. Noise, uncertainty and delay are the key factors which affects stability & transparency of haptic system and hence degrade the system's performance. In this paper, to maintain the stability and transparency of system under the presence of noise, uncertainty and delay, a PI controller has been designed for haptic interface. Performance of designed controller is observed by the simulation of haptic system using MATLAB Simulink®.

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Keywords: Haptic Interface; transparecy; stability; PI Controller; uncertainty; noise.

1. Introduction

Haptic system refers to the science of manual sensing (with the help of sensors) and manipulation of objects & environment in the virtual world and vice- versa [1]. The ultimate aim of field of haptic is to provide the user a sense of touch while interacting with simulated objects in virtual environment. To achieve this aim, it should provide minimum stiffness to free space and maximum to rigid space, so called transparency. It makes touch, a unique sense as like as human sense system and enable the bidirectional flow of energy which connect the virtual world with real. This bidirectional flow of energy may be in terms of force, velocity, displacement and sound, to feel realistic. For generation of feedback force or velocity or displacement, electric motors are used. The control mechanism for position & velocity is necessary as absence may cause oscillations or vibrations in the device which further affects the performance of the system and may cause physical threat to user. So it is important here to control this energy as

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well as maintain the transparency of the system.

Earlier, numerous work have been done to maximize the transparency and stabilize the system. Anderson and Spong [2] have used a passivity approach using tellegen's and lyapunov theorem to control force feedback operation including delay time. Hannaford and Ryu [3] have proposed a method in which active system behavior is to be measured and inject variable damping whenever net energy is produced by the virtual environment. Colgate et al. [4] proposed a passivity conditions for haptic system which includes virtual wall, haptic device and feedback controller. By using these results further the dynamic range of achievable impedance, Z-width, has been defined as a measure of performance and various factors affecting the Z-width have been discussed in [5]. Although these results are restricted within the case of virtual wall dynamics as the closed loop controller. Design methods of controller were not discussed in this. Later Adams and Hannaford [6], [7] represents haptic interface as two port device with terminals for human operator and virtual environment. In this, they also proposed the unconditionally stable condition that two port network that should be passive so the design procedure assures the stability of the system. This approach shows the advantage that we can decouple the design problem from the design of virtual world but it does not shows best transparent results. Other than this, passivity condition depends upon the dynamics of haptic display so this proposed method may not be applied to multi axis haptic system in which dynamics are changing according to haptic system. Zhang et al. [8] have proposed stable design method controlling the interface velocity to a reference and Eom et al. [9] have proposed a one DOF stable haptic system with adequate transparency but both systems does not consider the noise at operator's end which certainly affects system transparency. In [10] J.J Gill et al. have designed the specified range of stability condition of LHIfam one DOF haptic system under different values of delay but have not considered the uncertainty and nonlinearities in the system which is important in system's output response.

In this paper, a PI controller has been designed for one DOF haptic system with adequate transparency and stability considering the operator's noise, uncertainty and delay in the system. Noises and uncertainty in the system has been measured using disturbance observer proposed in [11]. The delay is average approximated from the expansion of Taylor's series as in [10]. The effectiveness of the proposed system has been verified by authors under the presence of different noise, uncertainty and delay conditions through simulation and results are presented later.

2. System Description

The haptic device studied in [12] gives brief about haptic real system which is composed of three elements: 1) the robot manipulator; 2) the virtual environment; and 3) the virtual coupling network, as shown in Fig. 1. The robot manipulator is the mechanical device which is operated by human operator. A virtual environment is the computer generated model of a real scene. It is responsible for interaction between objects and environment in the virtual world.

A spring damper model is considered as virtual coupling network that defines the virtual force, which must be restored to the human operator as a function of velocity and position of both the user and the virtual object. This kind of virtual coupling network is called as impedance model of the haptic interaction as shown in Fig. 1.

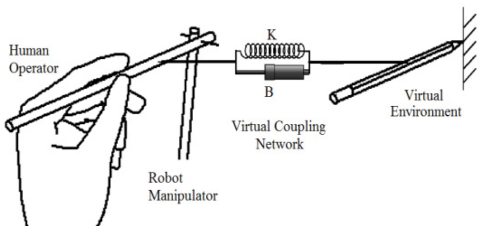

Fig. 1: Spring damper model of haptic system [12]

Here K and B are the stiffness and damping coefficient of virtual coupling network which is used to compute the force of the virtual environment. The values of these coefficients should be as high as possible to ensure the transparency of the system [12], because if we choose lower values, it results, the virtual environment will feel soft.

However in case we choose very high values of *K* and *B*, the system may become unstable. Hence choice of *K* and *B* is an important factor to ensure transparency and stability.

To analyze this mechanical model, an electrical equivalent is to be considered. There are lots of benefits of an electrical model over mechanical in terms of analysis. A model as shown in fig.1 can be reconstructed with the view of electrical control interface as in fig. 2. Here, *P*(s) is electrical equivalent model of mechanical interface between force input and velocity output as in (1)

$$P(s) = \frac{1}{ms + b} \tag{1}$$

where *b* and *m* are the physical damping and mass coefficient for the haptic interface respectively. The relation between physical damping and mass cannot be supposed to be arbitrarily large. In [13], authors have investigated the stability range for values of *m* & *b* for different haptic devices.

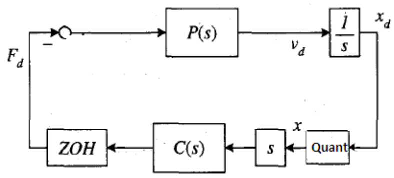

Fig. 2: Interface model of Haptic System

The velocity signal received from the output of plant transfer function *P(s)* is then integrated and quantized bef ore giving to the virtual environment as it work on digital signal. A virtual coupling network is a spring damper equivalent for electrical analysis as given in (2)

$$V(s) = \frac{K + Bs}{s} \tag{2}$$

where *K* and *B* are the spring stiffness and damping constant for virtual coupling network.
The controller *C*(s), is generally implemented by having the same dynamics as of virtual wall of (2). Hence controller *C*(s) can be written as below in (3).

$$C(s) = B + \frac{K}{s} \tag{3}$$

Performance of haptic system can be described in terms of transparency and stability. Transparency here means the amount of input signal in terms of force or velocity, which is applied at input terminal of device that should reach to the virtual world, and in feedback cycle, amount of signal developed by the mutual interaction of objects & environment in the virtual world, should reach to user. In the haptic system, we construct a mathematical equivalent model for mechanical system. But the universe of mathematical models from where, model is chosen, is distinct from universe of physical system. So exact model, which includes physical plant, can never be constructed. To analyze the physical systems which are usually non-linear in nature, an equivalent model is constructed with few assumptions so that system becomes linearized. These assumptions may affect system performance and reduces the transparency and stability. Whereas higher transparency is desirable as it results into more realistic feel to the user. And show the stability here means response of system gets settled over certain period of time. In the absence of stability, system may start vibrating hence degrading the performance of the system.

In order to investigate the effects of uncertainty on haptic system performance, we have tried to incorporate them into the haptic system as shown in fig. 3. The uncertainty can arise in to the haptic system due to un-modeled dynamics, payload uncertainty, noise, computational delays. The un-molded dynamics can be represented as w(s) uncertainties can be modeled as delta 'Δ' varies in range $-1 \le \Delta \le 1$and a fixed transfer function *W(s)* as given below in (4).

$$w(s) = \alpha ms + \beta b \quad (4)$$

where α and β are constants; b and m are the physical damping and mass coefficient for the haptic interface respectively.

Delay plays an important role in the working and synchronizing of haptic system. It sometimes is necessary for synchronizing the different processes of system and sometimes it degrade the performance of the system. Delay appears into the system because of various reasons such as quantization, computation and sample & hold circuit. When operator applies the force input to the haptic system, some noise would generate at the surface while interacting with haptic device. This noise may affect the transparency or stability if high, of the system. So, noise should also be consider while designing the controller for haptic interface.

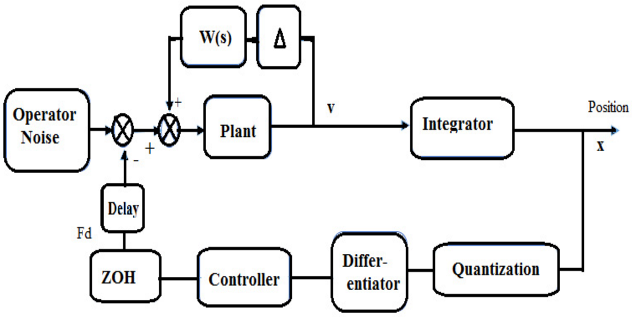

Fig. 3: Haptic system including delay and uncertainty

3. Simulation & Results

A simulation model of one DOF haptic system has been developed using Math-Works Simulink®. Various experiments have been performed for phantom 1 DOF system model including uncertainty, delays and noise at operator's end. A *PI* controller has been employed and tuned to control the stability and transparency of the system. Parameter of *PI* controller are calculated using Ziegler Nichols method [14] and manually fine-tuned to improve the output response. The sampling rate is set to 0.001 second. A nominal mass and viscous friction coefficient for the virtual wall are taken as m= 0.01 Kg and b=0.022 N sec/m, the values of constants are chosen as $\alpha = 0.5$ & $\beta = 0.5$ and uncertainty, Δ=1. Various other parameters of the system are taken as given in table 1.

Table 1. System parameters.

Parameters	Variables	Values
Mass	m	0.01
Physical damping	b	0.022
Virtual Stiffness	K	800
Virtual Damping	B	17
Sampling Period	T	0.01
Delay	t_d	0.01

3.1. Case 1: System in ideal condition with random parameters of controller

First, a system model is designed using Math-Works Simulink® with fixed force input shown in fig 4. In this case, uncertainty, delay and noise at operator's end, is not considered i.e. system is simulated in ideal conditions, nominal values of stiffness *K (equivalent to I of PI controller)* & damping coefficient *B (equivalent to P of PI controller)* for spring damper model of haptic system are taken as *1000 N/m & 1 N sec/m* respectively as in [9]. Various output responses for operator force, error signal, equivalent force feedback and position signal, are plotted in Fig. 5, 6, 7 & 8 respectively. These plot shows stable response but having high initial oscillation and settling time *0.37 seconds*. These initial oscillations affects the transparency and degrade the performance of the haptic device & system connected to it, so these should be as low as possible.

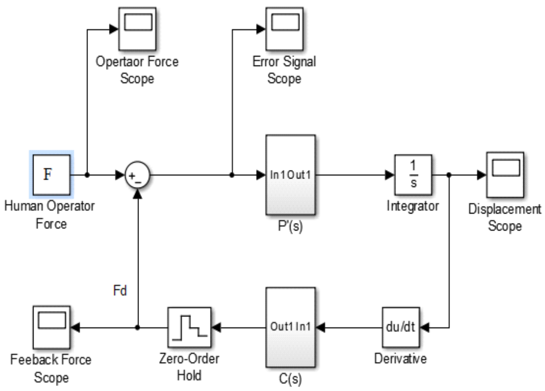

Fig. 4: Simulation model with fixed input force

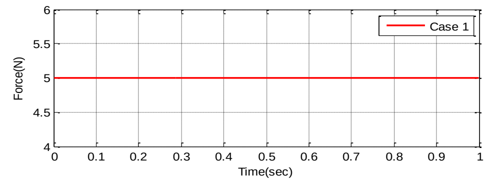

Fig. 5 Fixed input force

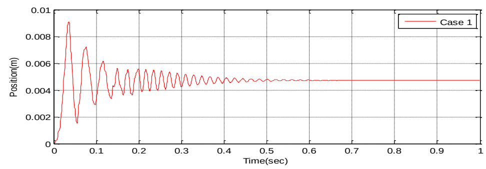

Fig. 6: Position response

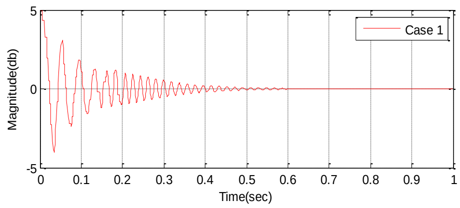

Fig. 7: Error response

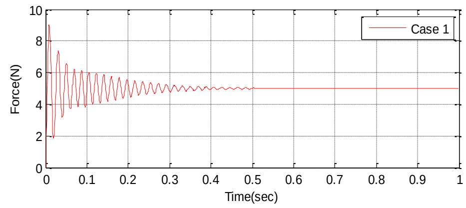

Fig. 8: Force response

3.2. Case 2: System in ideal condition with tuned parameters of controller

In this case, *PI* parameter of controller are tuned, for the haptic system model defined in *case 1*, as obtained by Ziegler Nichols method and manually fine-tuned to improve the results to *P=17* and *I= 800*. These parameters gives stable output responses for error, equivalent feedback force and position responses as shown in Fig. 9, 10 & 11 respectively. The settling time for error response is observed as 0.05 seconds from fig. 11.

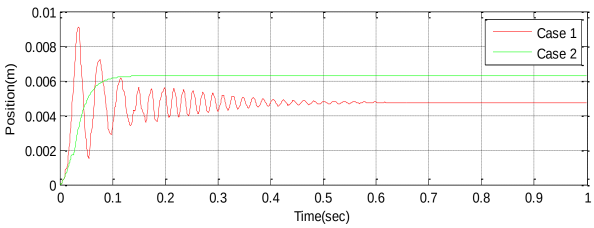

Fig. 9: Position response

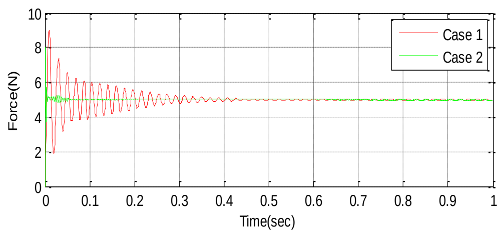

Fig. 10: Force response

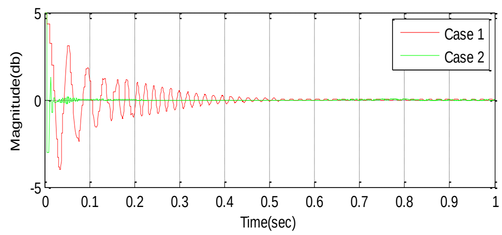

Fig. 11: Error response

3.3. Case 3: System with uncertainty, delay and effects of sampling time on system response

In this case, effects of uncertainty and delay has been considered into the system as shown in of fig 12. Simulation is performed with same tuned parameters of controller as described in *Case 2* i.e. *P =17 and I=800*. It is observed from fig.14, that, settling time for error response is increased from 0.05 of previous case to 0.06 after addition of delay into the system. Integration of these parameters into the system, also affects the behaviour of position and feedback force response in terms of increased in oscillation during initial period as shown in fig. 13 and fig. 15 respectively. Hence there is need for fine tuning of controller parameters to improve the performance of system.

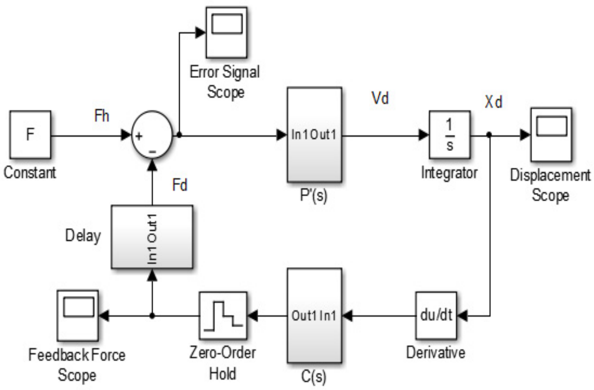

Fig. 12: Simulation model with delay and uncertainty

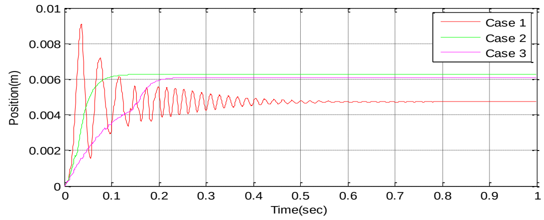

Fig. 13: Position response

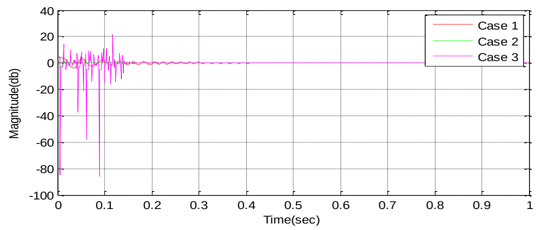

Fig. 14: Error response

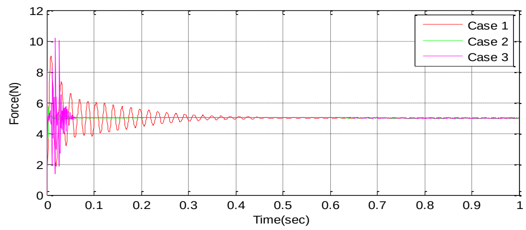

Fig. 15: Force response

Sampling time is an important factor which affects the stability of the system. It have key role to reconstruct the signal from discrete time domain to continuous domain and vice-versa. Sampling time in our model is 0.001 seconds [13]. For estimating the range of sampling time for a stable system we have performed some experiments for Fig. 12. When we are increasing the sampling time from 0.001 seconds then up to 0.00125 second, we have got tolerable results but when we further increased sampling, system gets unstable at 0.0013 second. When we decrease the sampling time below 0.0005 seconds, system starts getting instable. With the help of this experiment, a range for sampling time from *0.0005 seconds to 0.0013 seconds*, have been obtained for a stable system.

3.4. Case 4: System with uncertainty, delay and noise

In this case, an addition of noise entering at operator's end during the interaction of user with device, is also considered as compare to simulation model for haptic system described in *case 3* as shown in Fig. 16. The noise factor as Gaussian noise, has significant impact on transparency of haptic system, as incorporation of this factor has increased the settling time from 0.06 seconds of *case* 3 to 0.074 seconds as shown in fig. 19. It also increase the number of oscillations in initial region in force responses shown in fig. 18.

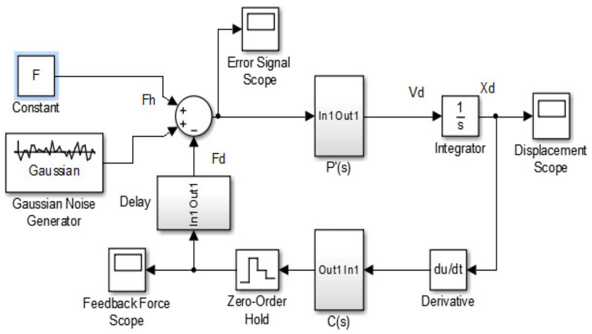

Fig. 16: Simulation model with delay, uncertainty and noise

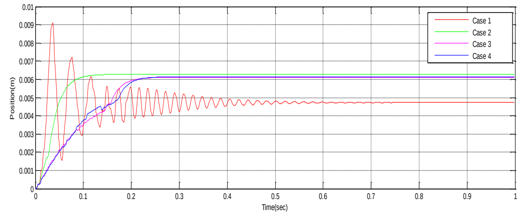

Fig. 17: Position response

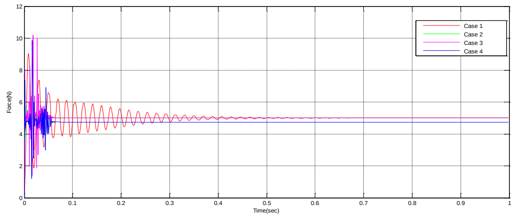

Fig. 18: Force response

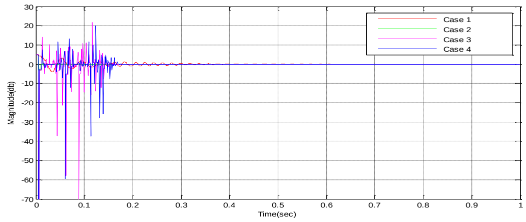

Fig. 19: Error response

3.5. Case 5: System under uncertainty, delay and noise with tuned parameters of Controller

In this case, *PI* parameters for controller has been calculated for simulation model shown in fig. 16, by Ziegler Nichols method and manual fine-tuned again for better performance as 12 & 1000 respectively. By simulation, we have error, force & position responses as shown in Fig. 20, 21 & 22 respectively. These plots show stable responses. Analysis of these plot shows the significant improvement in settling time in error, position and force responses. Settling time for error response is reduced to 0.041 seconds as of 0.074 seconds in *case 4*, which indicates the increase in transparency of the system.

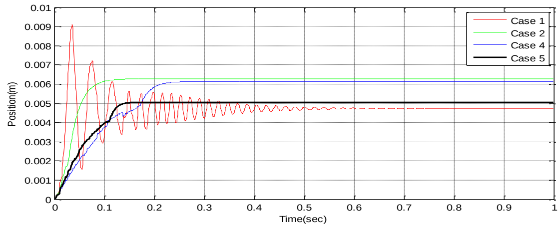

Fig. 20: Position response

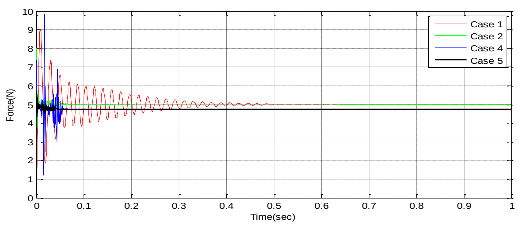

Fig. 21: Force response

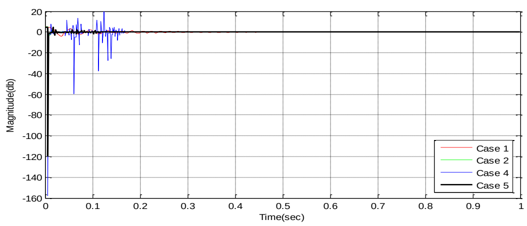

Fig. 22: Error response

4. Conclusion

In this paper, design of the haptic interface controller has been presented for one DOF haptic system. A *PI* controller has been employed to stabilize the haptic system using Ziegler Nichols method. We have incorporated the various uncertainties and unmolded dynamics, delay and noise at operator's end, while designing the haptic simulation model and their effects on performance has been analyzed. It has been observed that, the inclusion of these uncertainties into the system affects the system's response and degrades the performance and hence results into decreased transparency with increase in settling time. An effort has been made to improve the performance of haptic system under the presence of these uncertainties by the well-designed fine-tuned *PI* controller. For more improvement in results, modern optimizing technique can be used to find the parameter of *PI* controller such as GA and PSO can be employed in future.

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